

# THE DEEP ARGO PROGRAM: BROAD-SCALE SAMPLING OF THE FULL OCEAN WATER COLUMN

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## ABSTRACT

The Argo Program has revolutionized large-scale physical oceanography through its contributions to basic research, national and international climate assessment, education, and ocean reanalyses and forecasting. Nevertheless, Argo presently samples only the upper half of the ocean volume. Recent advances in profiling float technology and in the accuracy and stability of float-mounted conductivity/temperature/depth sensors have made it practical to obtain profiling measurements to 6000 m. By sampling from the sea surface to the bottom, global budgets of heat content, freshwater, and steric sea level can be closed, and the full-depth ocean circulation, including deep transports by the Meridional Overturning Circulations, can be observed systematically. International partners in the Argo Program are now deploying regional pilot arrays of Deep Argo floats in the North Atlantic, Southwest Pacific, and Indian/Southern Ocean to demonstrate the technical readiness and scientific value of the platforms and sensors. In the coming years these regional demonstration arrays will expand to form a 5° x 5° global array of 1228 Deep Argo floats. Deep Argo will deliver global data from the sea surface to 6000 m, in near real-time and research-quality versions, via the Argo Global Data Assembly Centers.

## 1. BACKGROUND

The foundation of the Argo Program is profiling float technology, including its continuing innovations. The history of neutrally-buoyant floats in oceanography began with short-range acoustic tracking by John Swallow in the 1950's (Swallow, 1955). Floats were transformed into global ocean circulation tools during the World Ocean Circulation Experiment, when R. Davis and D. Webb equipped them with a pumping system and satellite navigation, to cycle repeatedly from 800 m to the sea surface for tracking purposes (Davis et al, 1992). Subsequently CTDs were added to collect profiles of temperature and salinity during the ascents (Davis et al., 2001). The new profiling float technology was adapted and globalized for the Argo Program (Roemmich and Gould, 2003), and today it is taken for granted that systematic observations of the global upper-ocean (0 – 2000 m) are obtained by about 3900 Argo floats (Figure 1), and made available in near real-time.

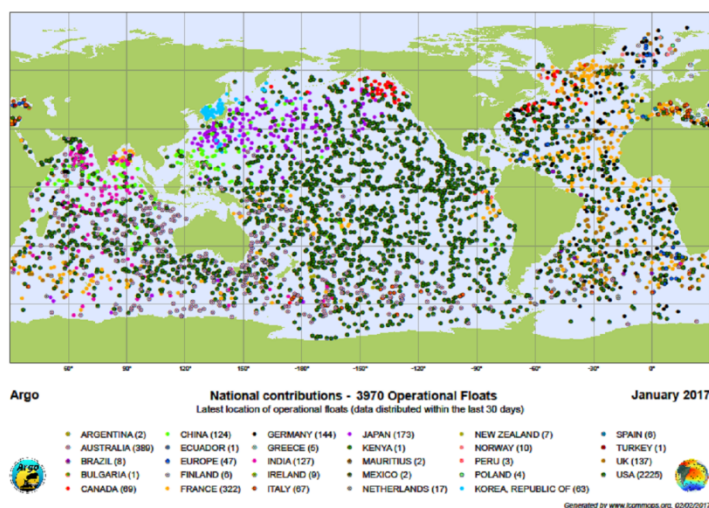


Figure 1: Location of 3970 active Argo floats as of January 2017 (Source: JCOMMOPS Argo Information Center)

Technology advances have continued under Argo, with Iridium communication improving the vertical resolution of profiles and the sampling of the mixed layer. Iridium greatly reduces the bio-fouling and grounding hazards to floats by shortening the sea surface time from 12 hours to 15 minutes. To underline the robustness of present float technology, a recent voyage of RV Kaharoa in the South Indian Ocean deployed 118 Core Argo floats without a single failure. A new generation of Argo floats is smaller, lighter, easier to handle, more robust, and longer-lived than its predecessors. Continuous advances in CTD sensors (SeaBird SBE-41 and 41cp) have made the Argo dataset more accurate and consistent than seemed possible 20 years ago when Argo

was conceived. The development of new biogeochemical sensors promises to add valuable multi-disciplinary dimensions to Argo in the future. Finally, Argo is no longer constrained to the upper 2000 m. Deep Argo floats and their accompanying new SeaBird SBE-61 CTDs are capable of profiling to 6000 m depth while achieving the accuracy in temperature, salinity, and pressure needed to resolve decadal variability and change in the deep water masses of the World Ocean. Here the technical status and future plans of the exciting Deep Argo Program are summarized.

## 2. MOTIVATION

Keys to understanding decadal variability and multi-decadal change in the oceans and the coupled climate system include observations of regional balances and completion of global budgets of heat, freshwater, sea level, and carbon. In regional balances, deep ocean heat and freshwater content are slowly modified by horizontal and vertical advective processes and mixing. The Meridional Overturning Circulations (MOCs) span the full water column as the flows of North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) away from their source regions are balanced by shallower and less dense transports of deep, intermediate, thermocline, and surface waters. Integration from the ocean bottom to the surface provides the full steric contribution to sea level as well as completing the ocean inventories of heat and freshwater content. An example of the high value of global observations is seen in estimates of global ocean heat content, which dominates the Earth's energy balance over terrestrial, atmospheric, and cryospheric components (Rhein et al., 2013) and whose decadal and longer changes are measured more accurately by ocean temperature than via the Earth's radiation budget (Johnson et al., 2016). A significant fraction of the ocean heat gain, perhaps 15% (Purkey and Johnson, 2010) resides in the deep ocean below Core Argo's 2000 m limit. Multi-decadal changes in properties often extend to the sea bottom through the spreading and renewal of AABW and NADW in all oceans. A Global Ocean Observing System must span the entire volume of the ocean, and technology limitations that previously made this impractical to implement with profiling floats are now being overcome. Line-based shipboard repeat hydrography, which until the present has been the dominant component of deep ocean observations, can now be complemented with area-based float observations. The combination of high accuracy transect-based repeat hydrography and broad-scale coverage by profiling floats is a powerful one. The need for systematic and accurate sampling of the full ocean volume has long been recognized by the scientific community (e.g. Fischer et al., 2010), and this is now a reality for addressing ocean circulation, heat, freshwater, and sea level issues on a genuinely global basis.

## 3. TECHNOLOGY REQUIREMENTS AND PROGRESS

Measuring the variability of temperature and salinity in the deep ocean is technically challenging. Deep-ocean properties show significant large-scale trends on decadal time scales in some deep basins, with the strongest anomalies occurring at high latitudes (Purkey and Johnson 2010; Purkey and Johnson, 2013; Desbruyeres et al., 2016) near water mass formation regions. Globally, multi-decadal depth-dependent trends below 2000 m are  $4$  to  $8 \times 10^{-3}$  degrees/decade in temperature (Purkey and Johnson, 2010). In salinity, if the global oceans are receiving 2 cm/decade of freshwater from melting ice (e.g. Johnson and Chambers, 2013), then the depth-averaged salinity is decreasing by .002 per decade. Regional signals are much larger than these global averages. The global challenge is substantial, and requires limiting the systematic errors in salinity and pressure to the greatest extent possible for estimation of the decadal trends in  $T(z)$  and  $S(z)$ . The Argo Program's international partnership proposes to meet the technical challenge by deploying a new generation of Deep Argo floats and CTDs in a global array. At present, Argo operates a total of 3970 floats, evenly distributed over the global ocean (Figure 1), measuring temperature and salinity profiles to 2000 m depth. Deep Argo will extend this Core Argo sampling to the ocean bottom.

A sustainable multi-national Deep Argo Program will not rely on a single float design. Technology advances have provided pumping systems and other float components capable of operation at abyssal pressures. Four models of Deep Argo floats have been developed (Figure 2), including two 6000 m models, Deep SOLO (U.S.) and Deep APEX (U.S.), and two 4000 m models, Deep Arvor (France) and Deep NINJA (Japan). Deep APEX is designed and manufactured by Teledyne Webb Research. Deep SOLO is designed and produced in limited quantity by the Argo float lab at Scripps Institution of Oceanography, with

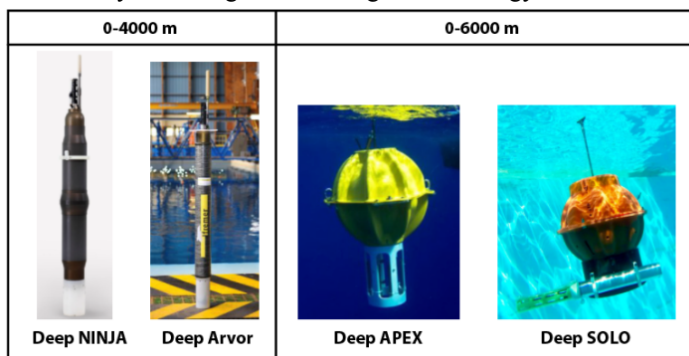


Figure 2: Deep Argo float models.

a commercial version by MRV Systems LLC. Deep Arvor (Le Reste et al., 2016) is designed by Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) and commercialized by NKE-Instrumentation. Deep NINJA (Kobayashi et al., 2013) is developed jointly by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Tsurumi Seiki Co. Ltd. Comparisons of these Deep Argo float models are ongoing, to assess float performance, robustness, and cost-effectiveness.

Conductivity temperature depth (CTD) sensors mounted on Deep Argo floats include an extended depth version of the SeaBird Electronics SBE-41 on Deep Arvor and Deep NINJA and the newly developed (SeaBird) SBE-61 CTD mounted on Deep SOLO and Deep APEX. Initial results from SBE-61 CTDs in the Southwest Pacific indicate that individual sensors are stable in abyssal potential temperature-salinity characteristics for more than a year, to about  $\pm 0.001$  psu at constant potential temperature (Figure 3). These instruments have not yet achieved their ambitious accuracy targets (0.001°C, 0.002 psu, and 3 dbar), but are making progress in approaching those standards. Additional validation experiments are planned for SBE41 and SBE61 CTDs. In Deep Argo, not only are the accuracies of individual instruments important, but as noted above, systematic errors must be minimized.

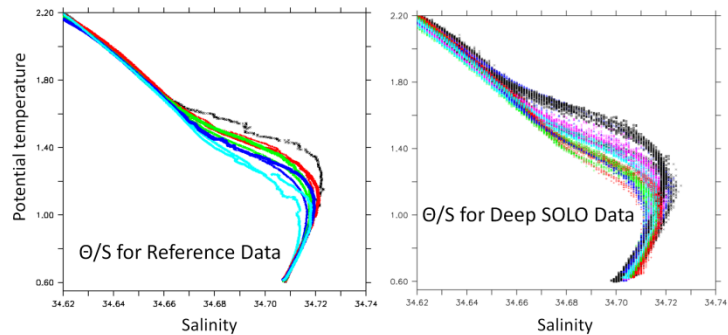


Figure 3: Deep  $\Theta/S$  relation for CTD reference data (CLIVAR line P15S in 2009, left panel) in the SW Pacific Basin and for 11 Deep SOLO/SBE-61 floats in the SW Pacific Basin (right panel).

#### 4. GLOBAL DESIGN OF DEEP ARGO

A Deep Argo Workshop was hosted by CSIRO in Hobart, Australia in May 2014 (Zilberman and Maze, 2015). Workshop objectives were to articulate the key scientific issues for Deep Argo, to plan the steps needed for implementation of a global Deep Argo array, and to determine the broad-scale coverage requirements for Deep Argo float measurements of temperature, salinity, and ocean circulation. Once it is fully implemented, Deep Argo will consist of about 1228 floats distributed globally at  $5^\circ$  latitude  $\times$   $5^\circ$  longitude spacing (Figure 4, from Johnson et al., 2015). Deep Argo floats will sample the water column from the sea surface to 4000 or 6000 m, depending on the float model used, every 15 days. A strategy for efficient combination of 4000 m and 6000 m float models in Deep Argo will be developed. Statistical analysis indicates that the  $5^\circ \times 5^\circ \times 15$  days array will greatly reduce uncertainties in the global decadal trends in ocean heat content, and the steric contribution to sea level rise (Johnson et al., 2015). The standard error of the trend in global ocean heat content for the 2000-6000 m depth range will decrease to  $\pm 3$  TW using Deep Argo data, down from  $\pm 17$  TW at present based on repeat hydrographic transects (Johnson et al., 2015). With 15-day cycling, the deep Argo array will have a refresh time, based on float battery energy capacity and consumption, of about 5 years, similar to past experience with 2000 m Core Argo floats.

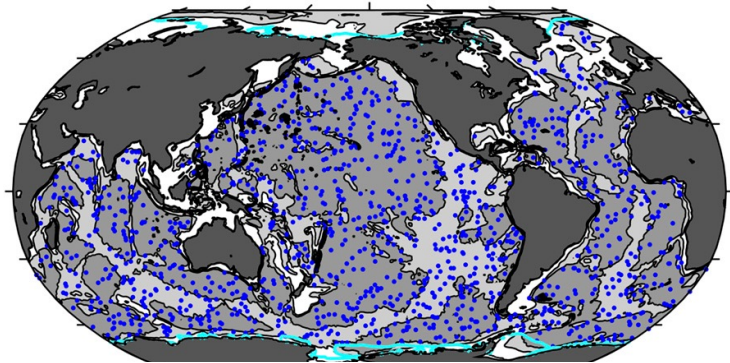


Figure 4: Conceptual plan for global Deep Argo implementation, based on average spacing of  $5^\circ \times 5^\circ$ . From Johnson et al (2015).

#### 5. REGIONAL PILOT ARRAYS

Deep Argo national programs are presently deploying regional pilot arrays whose purpose is to demonstrate the technical readiness, capabilities, and scientific value of profiling floats in full-depth global ocean observations, and to assess the accuracy of the float CTD data against the requirements for abyssal sampling. Results from the pilot arrays are being assessed to revisit the global design of Deep Argo and its objectives.

There are presently 30 active Deep Argo floats (Figure 5, upper panel), including 19 Deep SOLOs, 3 Deep APEXs, 2 Deep NINJAs, and 6 Deep Arvors. These floats, with many sampling to depths below 5000 m, are distributed among Deep Argo regional pilot arrays in the North Atlantic, Southwest Pacific, and the Indian/Southern Ocean. North Atlantic floats include the northern North Atlantic, where they are located near water mass formation regions, and along the 24°N (CLIVAR A05) repeat hydrography line, where meridional geostrophic transport in the Atlantic MOC can be compared with moored array observations, and where CTD reference data are available for assessment of SBE-61 profiles. Floats in the SW Pacific Basin are located along the pathway of AABW and NADW water masses spreading northward. Good CTD repeat hydrography reference data are available from three transects in this basin (CLIVAR lines P15S, P06, P16). At abyssal temperatures in the AABW layer the spatial variations of salinity on the 0.7°C potential temperature surface are less than 0.001 psu, making this a valuable water mass for comparison with SBE-61 float CTD data (Figure 3).

In addition to the presently active floats, plans have been registered with the Argo Information Center for 34 Deep Argo deployments in 2017 (Figure 5, lower panel), including 14 Deep SOLOs, 3 Deep NINJAs, and 17 Deep Arvors. Other 2017 plans are likely to emerge later in the year. The existing arrays in the North Atlantic and the SW Pacific Basin will be supplemented with additional floats for increasing their areal extent. The array in the South Australian Basin will be extended poleward into the Australian Antarctic Basin in early 2018 to observe AABW closer to its formation region. An additional pilot array is planned for the Brazil Basin in the South Atlantic in 2018. Overall, the locations of pilot arrays have been chosen to include regions having stable abyssal  $\Theta/S$  and ample hydrographic reference data for CTD validation, regions with previously identified abyssal warming trends, and regions close to water mass formation zones. In the next few years, the expansion of regional pilot arrays will continue, eventually filling the deep basins and merging to become the global Deep Argo array (Figure 4).

## 6. IMPLEMENTATION AND INTERNATIONAL PARTNERSHIP IN THE DEEP ARGO PROGRAM

The global implementation of Deep Argo will proceed along a very similar path to that followed by the Core Argo Program (Figure 1) in the early 2000's and will be closely coordinated with the continuation of Core Argo. Transiting research vessels will carry out most deployments, particularly in the Northern Hemisphere oceans. Repeat

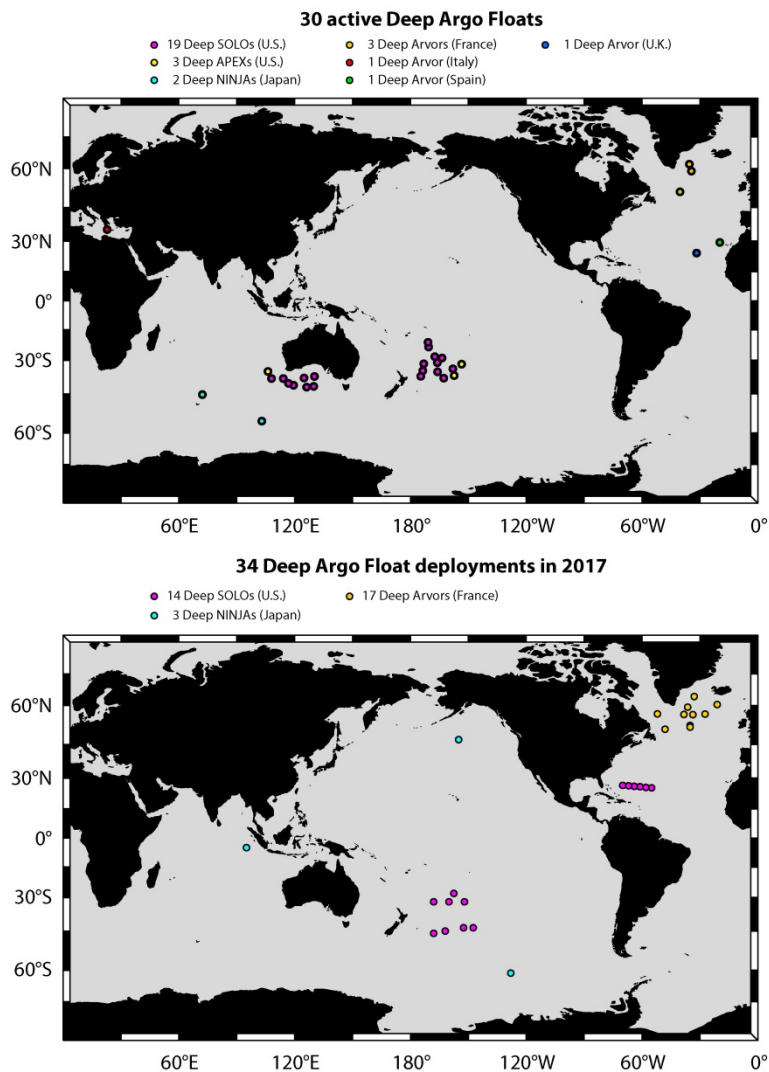


Figure 5: Maps of the Deep Argo regional pilot arrays including 30 floats that are presently active (upper panel) and 34 floats planned for deployment in 2017 (lower panel). Source: JCOMMOPS Argo Information Center

hydrography cruises are especially valuable for float deployment, as they additionally provide CTD reference data. In the South Indian and the South Pacific Ocean, and again similarly to Core Argo, there are not sufficient transiting research vessels or commercial shipping routes for broad area coverage, and the use of some dedicated deployment vessels is essential. In a collaboration of New Zealand, U.S., and Australia's Argo programs, the 28-m RV Kaharoa has deployed over 1500 Core Argo floats since 2004, across all of the South Pacific and South Indian Oceans, as well as most of the U.S. Deep Argo floats shown in Figure 5. The main respect in which Deep Argo implementation may differ from its upper-ocean counterpart is that it may prove necessary to recover some fraction of Deep Argo floats for recalibration of CTDs, in order to ensure adequate sensor accuracy. RV Kaharoa has already demonstrated the feasibility of Deep Argo float recovery, having recovered and redeployed four Deep SOLO floats in the SW Pacific Basin for a controller modification during 2016.

In the pilot phase of Deep Argo, floats from the U.S., France, Japan, New Zealand, the U.K., Spain, and Italy have been deployed (Figure 5). It is expected that more international Core Argo partners (Figure 1) will join the Deep Argo effort, some during the remaining pilot phase and some in global implementation. The Argo Steering Team will continue its coordination of Core Argo and Deep Argo, which are considered as a single global Argo array spanning the full ocean depth. As with Core Argo, all Deep Argo data are freely and immediately available from Argo's Global Data Assembly Centers. The era of systematic observations of the global ocean has arrived.

### **ACKNOWLEDGEMENTS**

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